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VELOCITY AND ENERGY OF THE TUNGUS METEORITE

(O skorosti i energii Tungusskogo meteorita)

by K. P. Stanyukovich
and V. A. Bronshten

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Investigations of the region of destructions having resulted from the fall of the Tungus meteorite on 30 June 1908 [1], and calculations of the shock wave parameters, having formed during its flight in the atmosphere [2], permitted to estimate the total energy of destructions as being $\sim 10^{23}$ ergs. The net picture of the radial fall of forest trees from the epicenter points to the dominating effect of the exploding wave, while the character of the fall itself, and in particular, the existence of a "zone of indifference" and of standing tree trunks ("telegraph poles"), undoubtly inducates that the meteorite's explosion took place in the air [1]. Thus, the assumption, advanced earlier (1925) by A. V. Voznesenskiy, and a little later by L. A. Kulik [3], about the overground character of the explosion, found its corroboration. The possible causes of the explosion will be examined below.

The motion of the meteorite in the atmosphere was examined by V. A. Bronshten [4] on the basis of known equations of meteoric physics [5, 6]. Solutions were obtained for the initial masses' range $10^5 - 10^7$ tons, and initial velocities of 11 — 46 km/sec, and also for the values of the resistance factor $c_x/2 = 0.5 \div 2$.

The values of meteorite's kinetic energy were calculated according to those of velocitiesand final masses of all the series of solutions. The comparison of the obtained values for E_k with the energy estimates brought up above indicates that the initial mass of the meteorite exceeded 10^5 tons in any case, and was likely to be within $10^6 - 10^7$ ton range, which would agree well, by the order of magnitude, with the Fesenkov's estimate, made on the basis of entirely different considerations, (see [8]).

Independently from the admitted value of the initial mass, the final velocities and the mass of meteorite must be included within the ranges: $16 < v_k < 30$ km/sec, $2 \cdot 10^4 < M_k < 7.5 \cdot 10^4$ tons.

The physical meaning of the independence of these estimates from M_o consists in the fact, that for matching magnitude E_k with the data on destructive energy in the region of the fall [1, 2] the admitted value of the resistance factor c_x must be raised simultaneously with that of the estimate of M_o, i.e. it must be considered that the greater mass undergoes the greater resistance in the atmosphere. The invsetigations by Ceplecha [7] of the Przibram meteorite have shown that for a large meteor body $c_x/2 = 0.43$, and therefore, the solution variant, corresponding to $M_o = 10^6$ tons, $v_o = 35 \div 43$ km/sec, $v_k = 30$ km/sec, $M_k = 2 \cdot 10^4$ tons, is most probable.

Let us pass now to the physical investigation of phenomena accompanying the flight of a large meteor body in the Earth's atmosphere.

When a body of a 25 to 30 m diameter moves at 120 km altitude with a cosmic velocity, a shock wave begins to form, at whose front the temparature T_y^o in the ideal case is determined by the relation

$$\frac{c_v}{\mu} T_y^0 = \frac{v^2}{2}, \tag{1}$$

where c_v is the heat capacity of the air (molar heat capacity), μ is its molecular weight ($\mu = 29$).

A more accurate formula for T_y^o, accounting for the adiabatic index variation $\gamma = c_p / c_v$, has the form

$$T_y^0 = T_1 \frac{p_2}{p_1} \frac{\rho_1}{\rho_2} = T_1 \frac{p_2}{p_1} \frac{\gamma - 1}{\gamma + 1}, \tag{2}$$

where $p_{1.2}$ and $\rho_{1.2}$ are the pressure and density respectively ahead and behind the front of the shock wave, T_1 is the temperature ahead of the front.

In a real case, the temperature at the shck wave's front T_y will be lower than T_y^o because of energy losses toward gas dissociation and ionization [10]. The values for T_y^o and T_y at various meteorite velocities are compiles in Table 1 hereafter.

TABLE 1

v, km/sec.		12	20	30	40	50	60	70
T_y^o according to	(1)	51 600	145 000	319 000	565 000	890 000	1 305 000	1 800 000
T_y^o "	(2)	45 700	139 000	330 000	589 000	940 000	1 400 000	1 970 000
T_y "	[10]	20 300	40 700	70 800	99 000	129 000	162 000	203 000

Thus, the temperature at the front of the Tungusk meteorite's shock wave constituted 70 000 ÷ 100 000°. The transition from T_y^o, determinable by formula (1), to the real temperature T_y, may be realized by the empirical formula

$$T_y = \eta T_y^0 v^{-0.7}, \qquad (3)$$

where $\eta = 2.27$.

The shock wave's radiant energy is

$$E_{iy} = \sigma S_i T_y^4, \qquad (4)$$

where σ is the Stephan-Boltzmann constant ; S_i is the radiating surface of the shock wave. It may be estimated that $S_i = \beta S_M$, where S_M is the surface of the meteorite, which at the first approximation we consider spherical, $\beta = 5 \div 10$. Inasmuch as

$$S_M = 4\pi\left(\frac{3}{4\pi}\,\frac{M}{\delta}\right)^{2/3} = 4\pi\left(\frac{3}{2\pi}\,\frac{E_M}{\delta v^2}\right)^{2/3}, \qquad (5)$$

substituting (1), (3) and (5) into (4), we shall obtain

$$E_i = \beta\sigma\,\frac{\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\left(\frac{\mu\eta}{c_v}\right)^4\left(\frac{E_M}{\delta}\right)^{2/3} v^{3.9}. \qquad (6)$$

Here, E_M is the total energy of the flying meteorite, δ is its density. At the given energy E_M the radiant energy increases in direct proportion to the velocity's fourth power.

In connection with this, it is necessary to note the fallibility of A. V. Zolotov's computations [11], having taken the bolide's color temperature (upper limit – 6000°) for the shock wave temperature, and attempting to calculate thereform the velocity of the flying body according to formula (1). It must be borne in mind, that at $T_y = 70\,000°$, the radiation maximum is situated in the ultraviolet part of the spectrum. For such a radiation air is practically non-transparent. However, ahead of the shock wave front there appears a heated zone with a considerably greater radiation surface, than that of the shock wave. At the same time, re-radiation takes place, and the temperature of the external zone will be lower than T_y, and its radiation will shift into the visible part of the spectrum. Part of this radiation is precisely received by the eye in the form of yellow-colored bolide. It is therefore obvious, that the tentative by A. V. Zolotov to determine the temperature of the shock wave according to bolide's color is inconsistent, while the computation of meteor body's velocity according that temperature simply makes no sense.

The utilization by Zolotov of the formula linking the light energy (luminous energy) of the explosion E_c with the light pulse is also unfounded:

$$E_c = \frac{I_c \cdot 4\pi R^2}{e^{-\mu(R-r)}}, \qquad (7)$$

where R is the distance from the explosion site, r is the radius of the illuminated region, μ is the light absorption factor in the atmosphere. The latter has been taken equal to 0.033 km^{-1}, to which corresponds an unusually high transparency coefficient $p = 0.93$, totally uncharacteristic for "taiga" regions*). If we only admit a more realistic, though still also high value $p = 0.80$, we obtain $\mu = 0.1$ km^{-1}, and all Zolotov's estimates change by few orders.

*) "Taiga" is the characteristic Siberian forest.

Let us now pause at the conclusion of a probable nature of the Tungusk meteorite explosion. The general heat balance equation for the meteorite has the form [10] :

$$\left(\Lambda \frac{\rho v^3}{2} + W_{изл}\right) S\,dt = E_{нагр} + \sigma (T^4 - T_a^4) S_м\,dt + QmNS_м\,dt, \qquad (8)$$

where [illegible]$_d$ is the density of the shock wave's radiation flux ; $E_{heat.}$ is the part of energy used for heating the body ; T and T_a are respectively the temperatures of the meteorite and of the atmosphere. S is the "midship" surface ; S_M is the surface of the body ; Q is the evaporation heat ; N is the number of vaporizing molecules ($cm^{-2} \cdot sec^{-1}$) ; m is the mass of the molecule.

Analysis of equation (8) shows that the second term of the left-hand part, conditioned by radiation, is much greater than the first one, which is conditioned by heat transfer at flowing about. The heat consumption in the evaporation process (third term of the right-hand part) is quickly becoming much greater than the heat consumption for the radiation from the meteor body's surface (second term), and that is why it is sufficient to examine the heat incoming at the expense of the radiation from the shock wave's front, and the heat consumed in the evaporation. Their dependence on the altitude is shown in fig.1 for an iron meteorite.

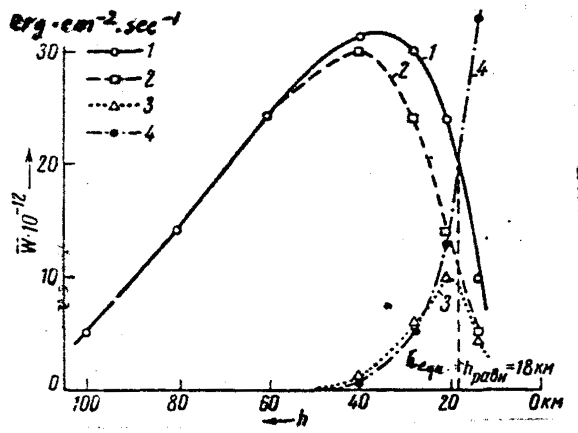

Fig.1. Energy balance during the motion of an iron meteorite : 1 — general energy receipt (iron, $v_0 = 60$ km/s, $i = 72°$, $r_0 = 10^2$ cm), 2 - energy receipt from the shock wave at the expense of radiation, 3 - energy receipt at the expense of the flowing around, 4 — consumption of energy on the evaporation.

As may be seen from figure 1 the receipt and consumption of heat are equalized at the altitude $h_{equ.} = 18$ km, the heating ceases, and then the body begins to cool off, and braking simultaneously, it reaches the Earth's surface. There will be the same picture for stone

But if we figure that we deal with the nucleus of a small comet, as Astapovich and Whipple thought in their times, and if we admit that this body, just as all comet cores are, is a conglomerate of methane-ammoniacal ice, also containing stone boulders and dust, the picture of phenomenas will be quite different. For an ice block at $r = 10^3$ cm, $v = 60$ km/sec, $i = 72^{o}$, the energy at 50 kn altitude ised for evaporation, is by one order lesser than that received by the body from the shock wave. As a result, the body is heated in depth more considerably, and it evaporates faster, i.e. the boundary of the evaporated layer is moving faster toward the center. A substantial mass of the matter (nearly 30%) is evaporated in a relatively short time (~ 0.2 sec.). If the process goes sufficiently fast, the evaporated particles may create, while outflowing, a strong spherical shock wave, and the phenomenon will bear all the characteristics of an extended explosion.

At a speed $v = 30$ km/sec, the power of the process ($2 \cdot 10^{13}$ ergs/g $\cdot$ sec) is comparable to powder explosion (10^{13} ergs/g $\cdot$ sec). Such phenomenon, studied in more detail by Stanyukovich and Shalimov [12], may be designated as "thermal explosion".

We have reviewed above the mechanism which may lead to the explosion at time of a single body's flight into the atmosphere. There is however also another possible viewpoint on the structure of comet cores. V. G. Fesenkov, for example, conside: the core of a comet as a dense cluster of comparatively small bodies.

Analysis of the direction of tree fall points with obviousness on the presence of not noe, but several centers of fall. This had already been revealed by L. A. Kulik. Taking this into account, Fesenkov proposed still another possible mechanism of destruction under the effect of the oncoming comet core, what the Tungusk meteorite unquestionably is.

At time of flight into the terrestrial atmosphere of a sufficiently dense swarm of bodies at cosmic velocity, the swarm may be surrounded by a general shock wave. However, at its penetration into the lower atmosphere layers, its density must decrease on account of mass difference, and consequently — of deceleration, and its transverse dimensions and "length" increase. As a result, each of the separate bodies or groups of bodies of a nearly similar mass will have individual shock waves. In this case, the process of destruction of the swarm's bodies will cease prior to their reaching the ground (because of surface per unit of mass increase), the shock waves having reached the Earth will cause the observed destructions, and radiation of a powerful shock wave will ensure the radiant burn of a series of objects, and in particular of trees.

In conclusion the authors wish to express their acknowledgement to Academician V. G. Fesenkov for his valuable discussions.

***** THE END *****

Committee on Meteorites
of the
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